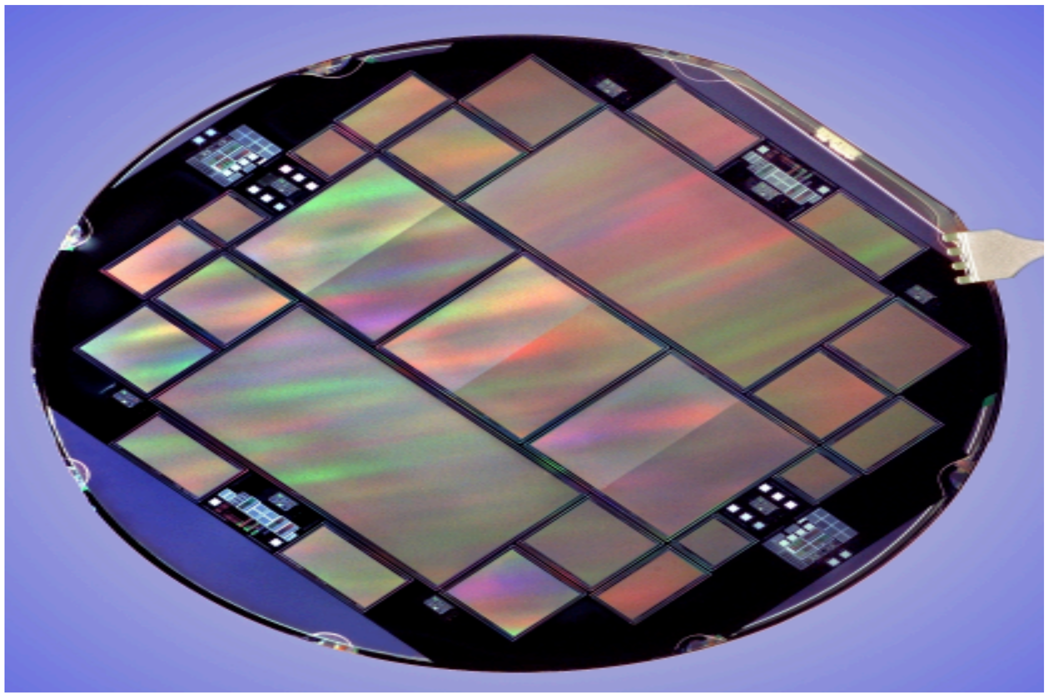
CCDs



Donna Kubik
Spring, 2005

References

1. “Fully Depleted, Back-Illuminated Charge-Coupled Devices Fabricated on High-Resistivity Silicon”, S. E. Holland, et. al., IEEE Transactions on Electron Devices, Vol. 50, No.1, January (2003) 225-238

2. “Determination of the electron-hole pair creation energy for semiconductors from the spectral responsivity of photodiodes”, F. Scholze, et. al., Nuclear Instruments and Methods in Physics Research A 439 (2000) 208-215

3. *CCD Astronomy*, Christian Buil, Willmann-Bell, 1991

4. *Scientific Charge-Coupled Devices*, J. R. Janesick, Bellingham WA, SPIE Press, 2001

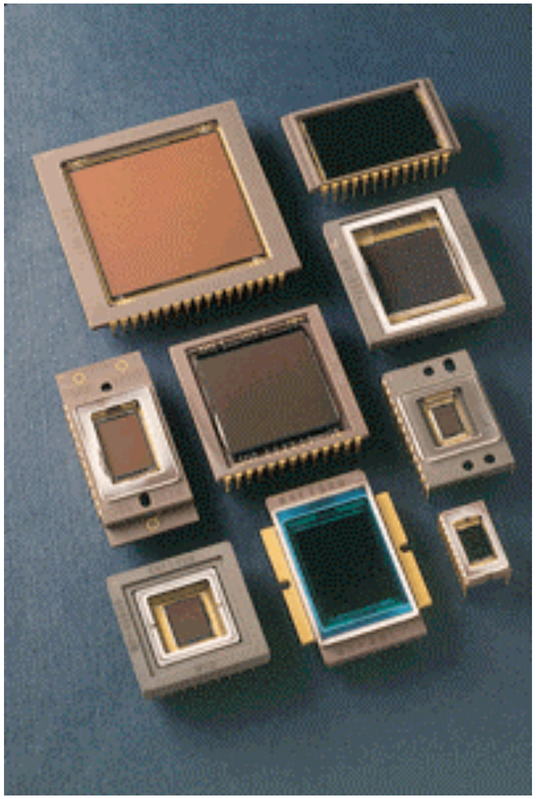
Charge coupled device (CCD)

- The CCD was developed in 1970 by Boyle and Smith at Bell Labs
- They were attempting to design a new kind of semiconductor memory for computers.
- At the same time they were looking for a way to develop a solid-state camera for use in video phones.

CCDs

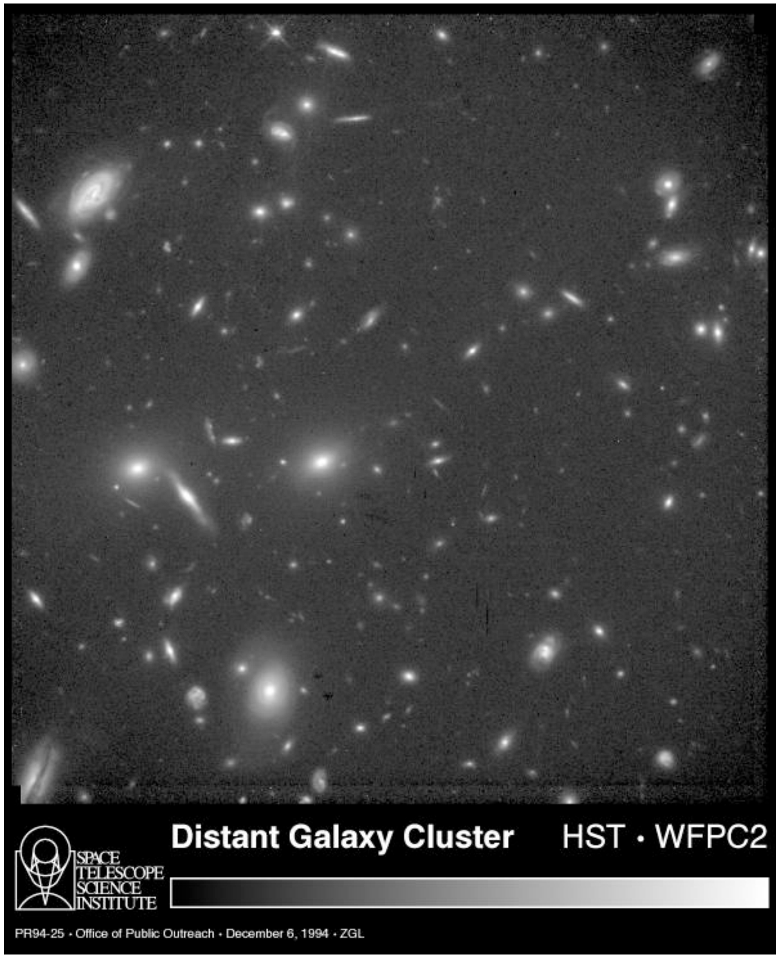
- CCDs are dynamic devices that move charge along a predetermined paths under control of clock pulses

- They now have applications in memories, logic functions, signal processing, and imaging



CCDs

- Like all photodetectors, CCDs can be used to detect photons or particles
  - CCDs are used for astronomical imaging
  - CCDs can be used as particle detectors (i.e. vertex detectors)

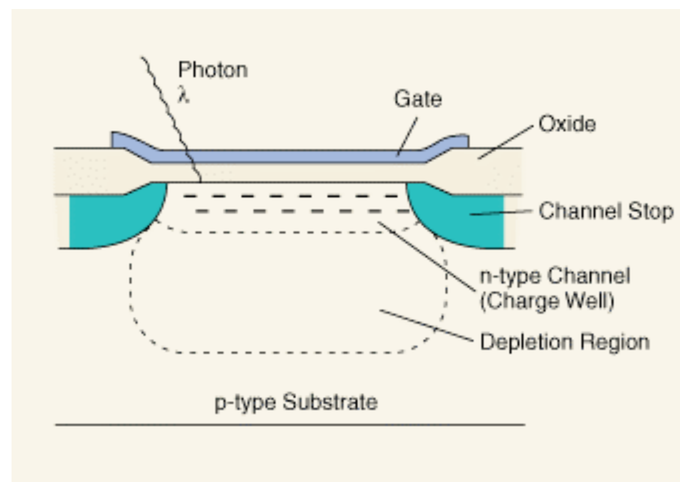


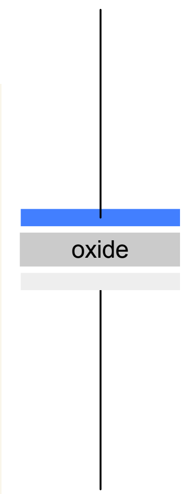
OUTLINE

- How does a CCD work?
- What are the basic characteristics of a CCD?
- What are the specific characteristics of the LBNL CCDs?
- What about CCDs as a vertex detector for the LCD?

CCD structure

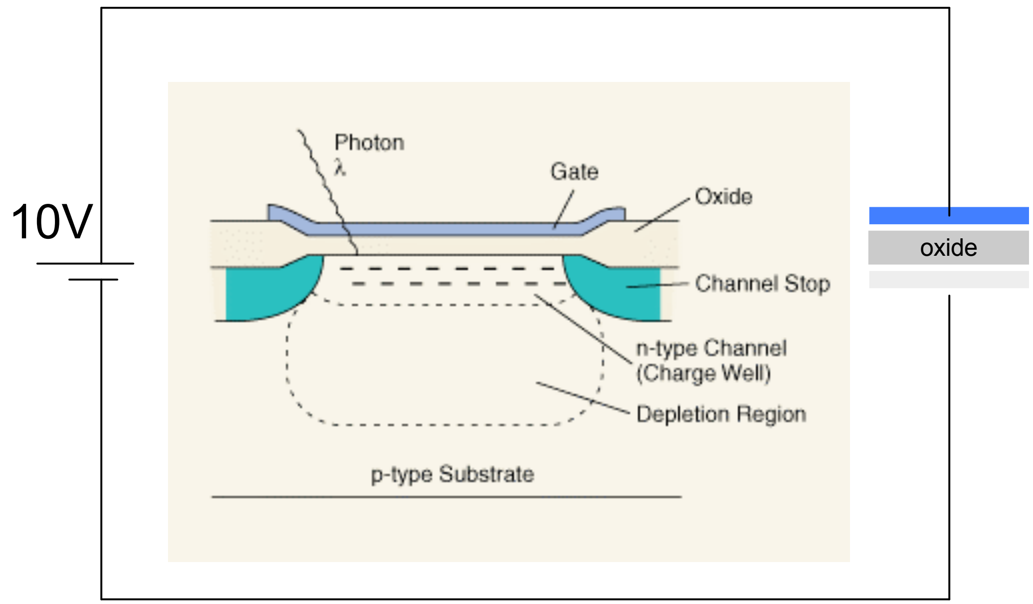
- MOS capacitor
  - metal-oxide-semiconductor
- Most common to use P-type substrate
- Holes are majority carriers in P-type
- There are a few electrons from thermal energy (minority carriers)





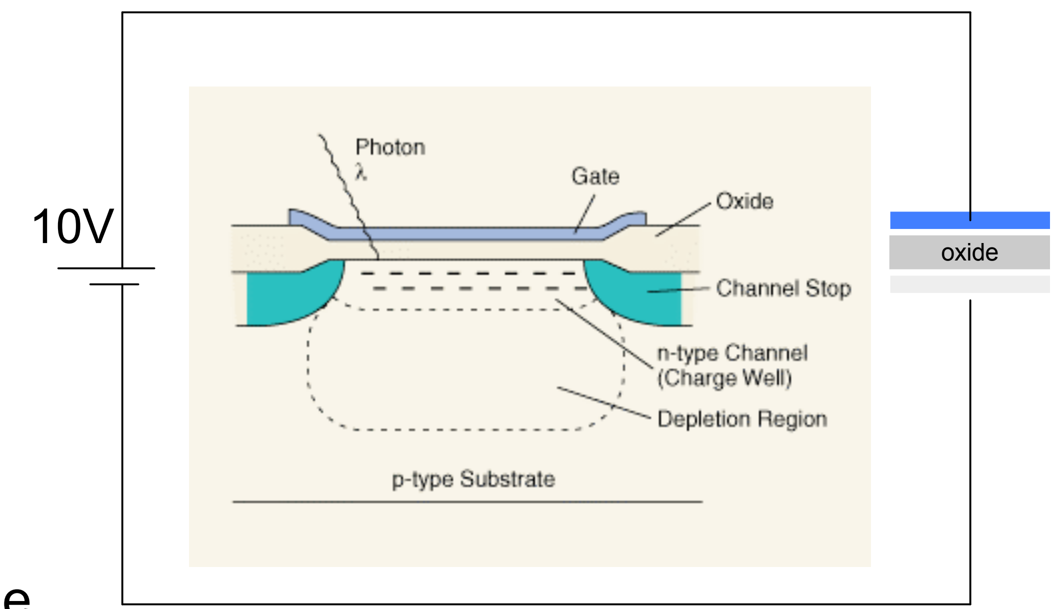
CCD operation

- Bias gate (typical 10 V)
- Majority carriers (holes) are pushed back into interior of substrate
- Zone almost free of majority carriers is then created at the SiO_2-Si interface (depletion region)



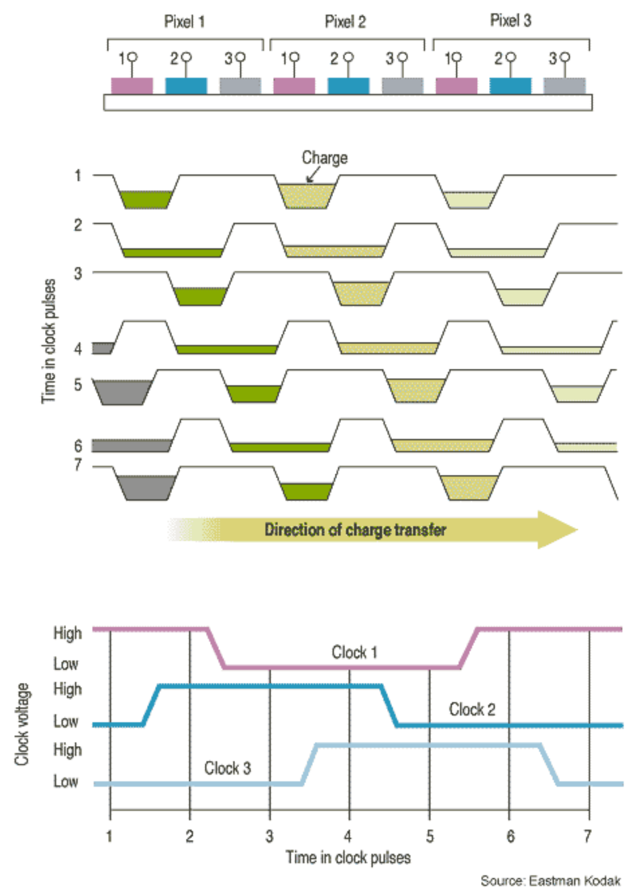
Charge injection

- e-h pairs created in the depletion region are separated by the potential
- The e- accumulate near the SiO_2-Si interface forming an n-channel
- This is also called the inversion layer
- The inversion layer carries the information

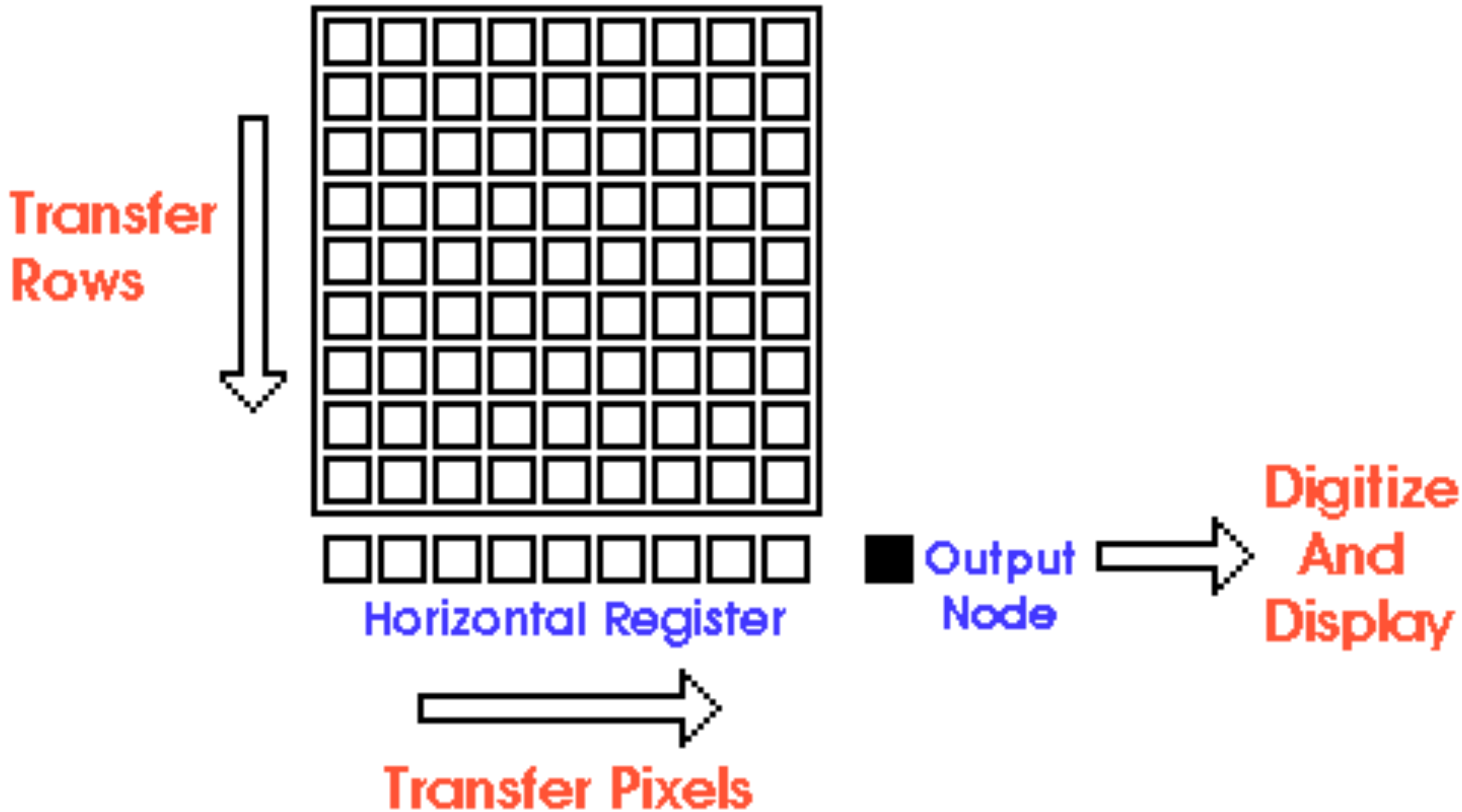


Charge transfer

- After the integration time has elapsed, the charges are read out
- Two phase, three phase, four phase
- Example shown is the most common, three phase transfer



CCD layout



Transfer
Rows
Horizontal Register
Output
Node
Digitize
And
Display
Transfer Pixels

CCD characteristics

- Quantum efficiency
- Spectral response
- Transfer efficiency
- Spatial resolution
- Linearity
- Blooming
- Dark current
- Sensitivity to cosmic rays
- Electroluminescence
- Cosmetic defects
- Noise

Quantum efficiency (QE)

- Quantum efficiency

$$QE = \frac{\text{average number of detected photons/pixel/second}}{\text{average number of incident phtons/pixel/second}}$$

- QE is generally <1.
- QE ranges from 40% to 80% for CCDs, compared to 2% to 4% for photographic emulsion.

Detective Quantum Efficiency (DQE)

- If a photon produces a photoelectron, the photoelectron will not necessarily be measured at the detector's output.
- The photoelectron could be lost in the transfer.
- So another measure, equivalent quantum efficiency or detective quantum efficiency (DQE) is often used.

Charge Collection Efficiency (CCE)

- QE can be > 1 for high energy photons.
- For example, a thinned CCD receiving a 1216 A photon averages 3 e-h pairs.
- To take this phenomenon into account, a new quality criterion was established to measure CCD performance when lit by energetic radiation (EUV and X-ray).
- This is called charge collection efficiency (CCE)
- SHOW GRAPH IN Scholze ARTICLE and next slide

Pair creation in Si

- Pair creation energy is a function of the incident photon (or particle) energy, E
- E < 1.14 eV pass through the CCD; i.e. Si is transparent in the far-infrared
- 1.1 eV < E < 3.1 eV (1126 nm to 400 nm) will generate a single e-h pair
- E > 3.1 eV will produce multiple e-h pairs when the energetic conduction band e- collides with other valence e-
- E> 10 eV:

$$\eta_i = \frac{E(eV)}{E_{e-h}}$$

where η_i is the ideal quantum yield

E_{e-h} is the energy required to generate an e - h

pair, which is 3.65 eV for Si at room temp

Hysteresis

- Local variations in QE may depend on past lighting (hysteresis).
- If the CCD was recently lit by intense light, those areas that were strongly lit have higher QE.
- To minimize this effect, can illuminate the entire array with a 700 nm source and then take many rapid readouts prior to exposure.

Spectral response

- Spectral response close to that of Si.
- Without any special “tinkering”, the spectral response is close to that of Si; the CCD can usually record radiation from 0.4 um to 1 um.
- The possibility of recording information beyond 0.7 um is new and important, for the eye and photographic plates are insensitive beyond that limit.
- The spectral sensitivity may also vary from pixel to pixel.

Transfer efficiency

- During the transfer from one stage to another, a certain number of charges is left behind

- A measure of the efficiency is termed charge transfer efficiency (CTE)

$$CTE = 1 - \frac{N_0 - N_t}{N_0}$$

N_0 is the number of charges under a gate

N_t is the number of charges under the following gate after the transfer

Transfer efficiency

- Only a slight inefficiency is tolerable
- If 1% of the charges is left behind after each transfer, a packet initially containing 100 electrons will contain only 37 electrons

$$100e^{-} \times (0.99)^{100} = 37\ \text{electrons}$$

- Today's large arrays, a packet must be moved an average of 500 times!
- CCD mfg are trying to reach a near-perfect rate
- Typical efficiency is 0.999990

Transfer efficiency

- CTE = f(temperature)
  - It temperature is too low, carrier mobility decreases and blocks operation of the CCD
- CTE = f(clock rate)
  - In astronomy, it is always possible to read the CCD slowly
- CTE = f(number of charges)
  - If <1000 e-, noticeable trapping
  - Pro: Saturate traps with LED flash (thermal current can also do this if only moderately cooled)
  - Con: Adds noise

Spatial resolution

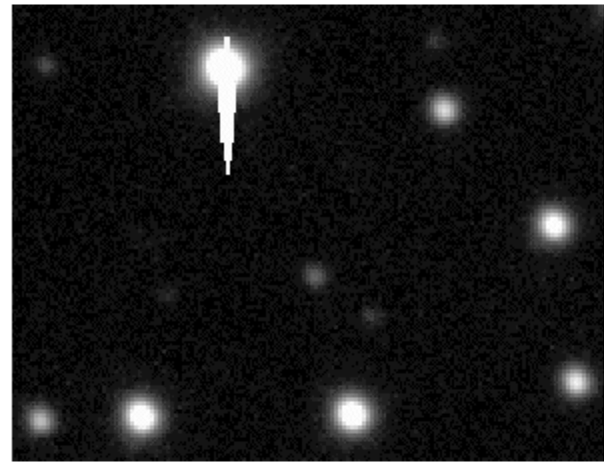
- Pixels 10-30 um long
  - Compare to 5 um grain size in emulsion
- Transfer inefficiency can dilute the charges of a pixel into the following pixels
- Diffusion of charges in substrate during integration
  - Especially for long wavelengths which have longer absorption lengths
  - Solution is to thin the P doped layer (substrate) so that they recombine in the supporting substrate
  - But this decreases red sensitivity

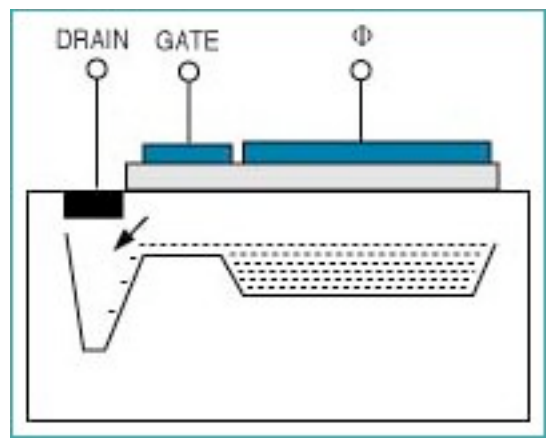
Linearity

- The linearity of a CCD is very good
- Linearity is limited to a working range of intensity
- For low illumination, linearity is no longer possible because of threshold phenomena, as charge trapping
- At high light levels, the detector becomes saturated
  - Space charge occurs in which e- repel each other an leak over into adjacent pixels causing blooming (next slide)

Blooming vs. antiblooming

- Anti-blooming gate designed to bleed off overflow from a saturated pixel.
- Without this feature, a bright star which has saturated the pixels will cause a vertical streak.





Dark Current

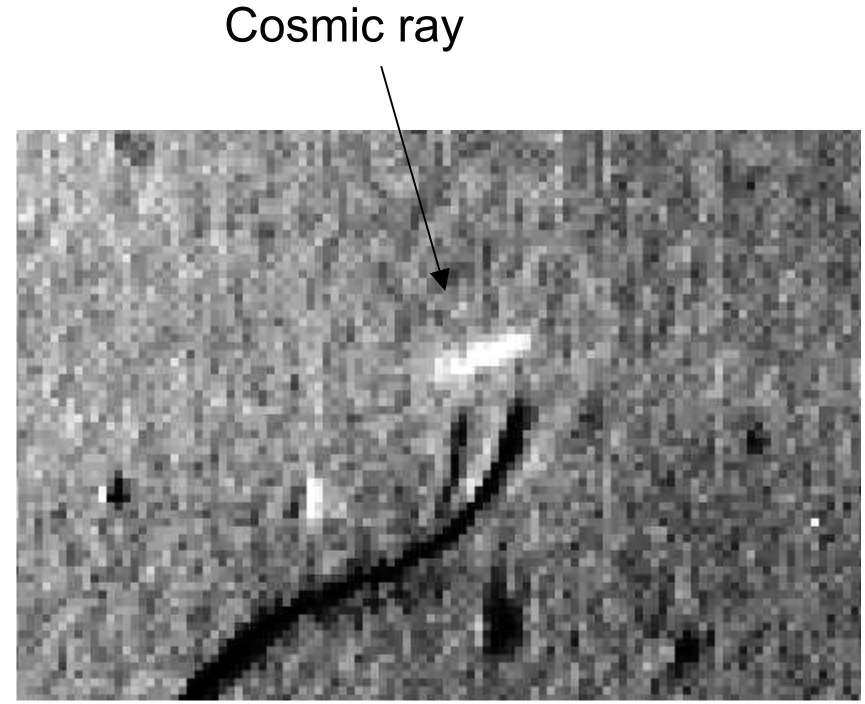
- Even if the CCD is in complete darkness, a signal is observable
- The signal is due to thermally created charges
- Main reason to cool a CCD is to minimize the dark current
- Production rate is such that, at room temperature, a standard CCD in darkness is saturated after only a few seconds of integration
- Dark current becomes nearly negligible at about -100 deg C
- Thermal signal decreases by a factor of 2 for a 7 deg C drop in operating temperature

Dark Current

- But if a CCD is cooled to a very low temperature, the Si characteristics change
  - In practice, a CCD is never cooled below -120 deg C
    - Decreased mobility
  - At low temperatures, the spectral sensitivity changes
  - A shift toward blue on the infrared side of response curve
    - Typical 2.5 Angstroms/deg C
- The thermal current comes from the Si-SiO_2 interface, so designers are trying to build CCDs where this effect is minimized (MPP, multi-pinned phase)

Sensitivity to cosmic rays

- Cosmic rays can interact with Si
- If it arrives on an angle, would leave a streak
- Increased problem at high altitudes and in space
- Can discriminate CR by comparing images of same field



Electroluminescence

- The output amplifier can emit a weak light by electroluminescence
- Solution is to turn off or lower amplifier voltage during exposure and then just turn it on immediately before readout

Cosmetic defects

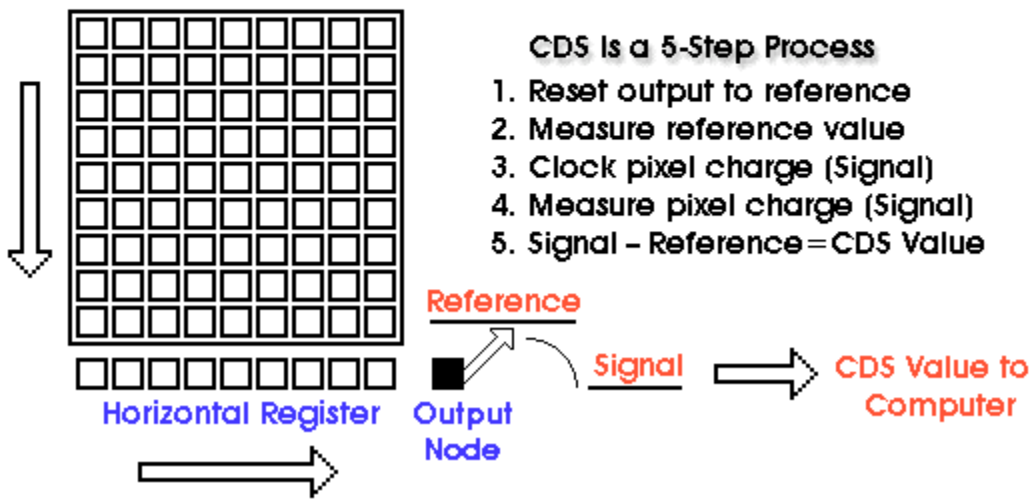
- A cosmetic defect is any defect locally affecting the quality of the sensitive surface
- Some pixels may have greater dark current than their neighbors (hot spots), a completely insensitive pixel (dark spot), or sometimes a defective column.
- Most CCDs have some defects
- Mfg offer several levels of quality
- 5 or 6 bad pixels uniformly distributed in an image or even a defective column can be tolerated and corrected during image processing

Noise

- There are many sources of noise
  - Thermal
  - Reset noise
  - Phonon (shot) noise
  - Readout noise

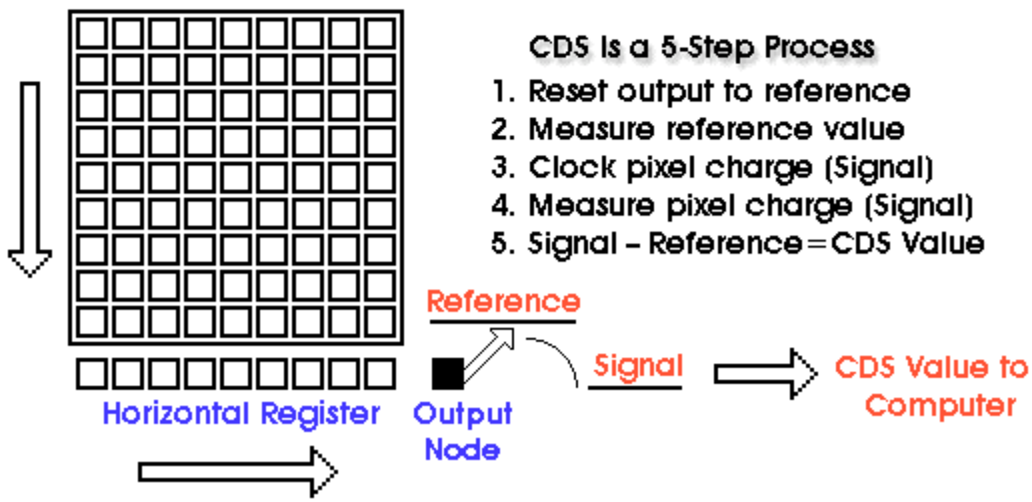
Correlated double sampling (CDS)

- Correlated double sampling yields the best representation of the true charge associated with each pixel
- From an electronics standpoint, there are different methods for accomplishing this, such as digital, analog sample and hold, integration, and dual slope.



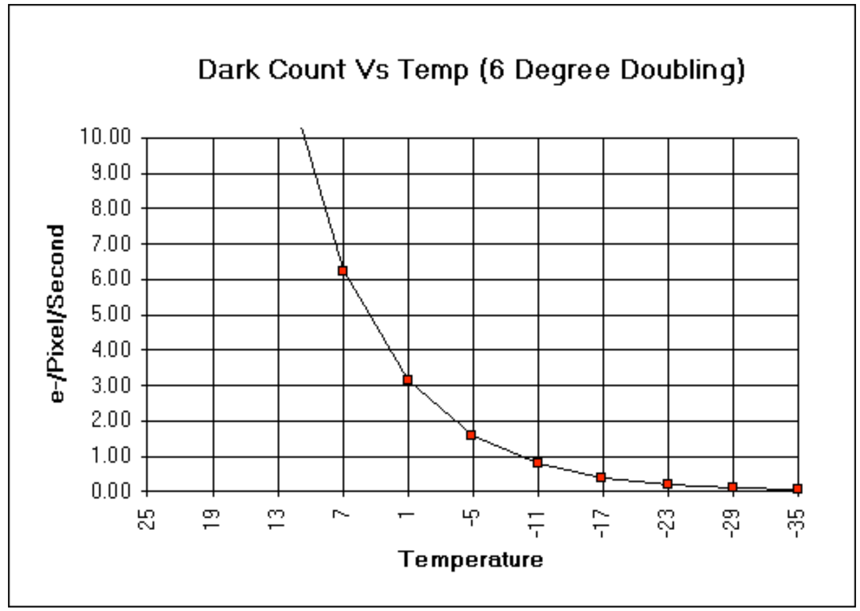
Correlated double sampling (CDS)

- Before the charge of each pixel is transferred to the output node of the CCD, the output node is reset to a reference value
- The pixel charge is then transferred to the output node. The final value of charge assigned to this pixel is the difference between the reference value and the transferred charge



Dark noise

- Although the dark count can be subtracted, the dark noise cannot. The dark noise is approximately the square root of the dark count. In this example, the dark noise is about 55 electrons.



Astronomical imaging

- LBNL has developed red-extended CCDs for high redshift surveys (Supernovae Cosmology Project, SNAP, DES)
- Extended red response is extremely important due to the use of distant, high redshift supernovae for the determination of cosmological parameters and for deep surveys
- Detection and follow-up spectroscopy of high redshift objects would greatly benefit from CCDs with improved near-infrared response.

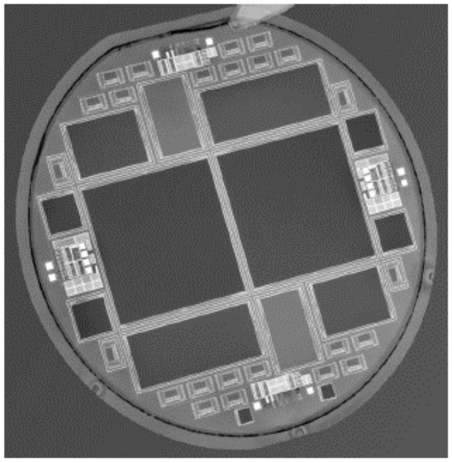
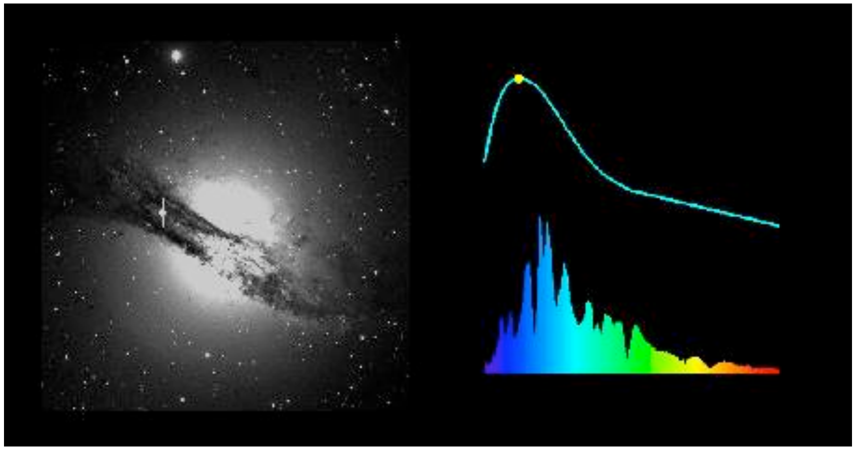
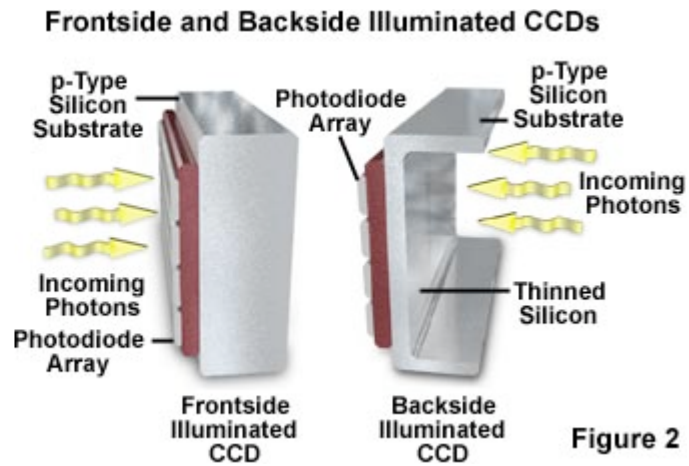


Fig. 3. A 100-mm-diameter wafer fabricated at LBNL. The two large CCDs in the center of the wafer are 2048 $\times$ 2048, 15 μm pixel, frame transfer CCDs.



Astronomical imaging

- The large focal planes of astronomical telescopes require high-QE, large-format CCD detectors.
- In order to achieve high QE, the standard scientific CCD is thinned and back illuminated



Frontside vs.backside

- Back-illuminated CCDs have exceptional quantum efficiency compared to front-illuminated CCDs
- To make a back illuminated CCD, take a front-illuminated CCD, thin it to ~20 μm, and mount it upside down on a rigid substrate
- The incoming light now has a clear shot at the pixel wells without the gate structures blocking the light

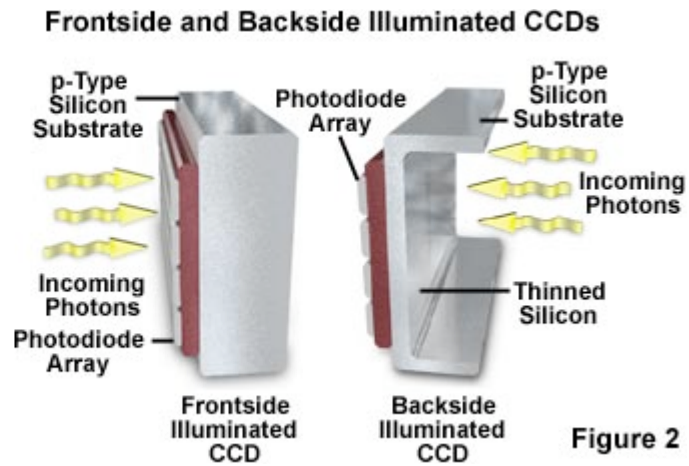


Figure 2

Thinning

- Thinning is required, because the relatively low-resistivity silicon used to fabricate scientific CCDs limits the depth of the depletion region.
- If left thick, the shorter-wavelength, short absorption-length photons will be absorbed before reaching the depletion region where the e-h pairs they create are more efficiently collected

Frontside and Backside Illuminated CCDs

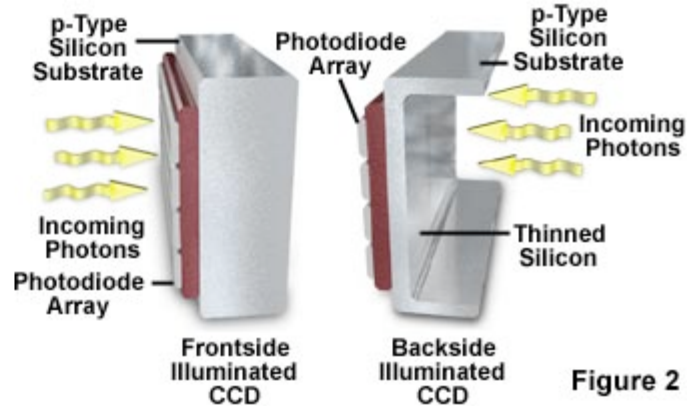
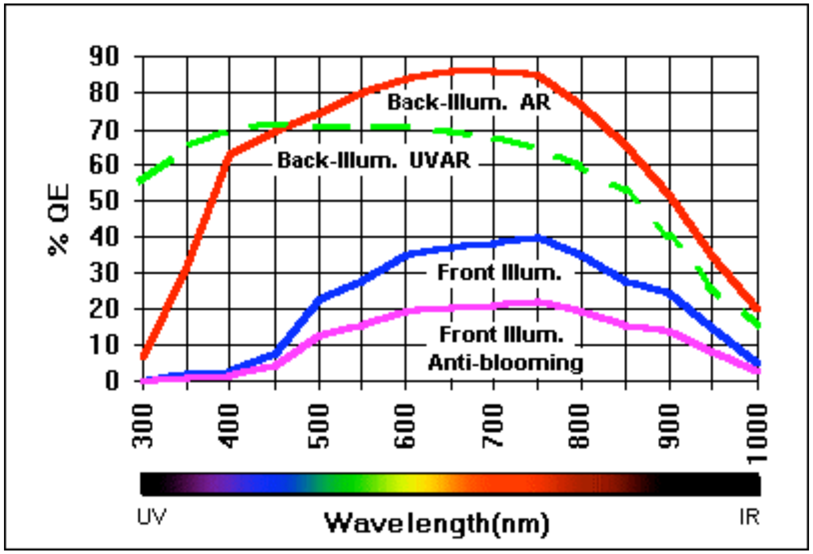


Figure 2

Back-illumination

- However, this process degrades red and near-infrared responses due to the rapid increase in absorption length in silicon at long wavelengths (next slide)
- In addition, fringing patterns due to multiply-reflected light are observed in uniformly illuminated images taken at near-infrared wavelengths where the absorption length exceeds the CCD thickness.
- Absorption length is the reciprocal of the absorption coefficient (next slide)



Typical Q.E. curves for front- and back-illuminated CCDs

Absorption coefficient

- The intensity of the photon flux, *F*, varies as a function of the thickness, *z*, of the silicon, following the relation

$$F(z) = F(0)e^{-\alpha z}$$

where α is the coefficient of intrinsic absorption of the silicon and *F(0)* is the incident flux on the silicon. Note: $h = 4.136x10^{-15}\, eV \cdot s$

λ(nm)	$\alpha(um^{-1})$ $T = 77K$	$\alpha(um^{-1})$ $T = 300K$	Energy (eV) $E = hc/\lambda$
400	5.0	4.0	3.10
600	0.5	0.25	2.07
800	0.1	0.005	1.55
1000	0.01	0.002	1.24

Absorption length

- 90% of the radiation penetrating the Si is absorbed after a distance

$$z_{90\%} = 2\alpha^{-1}$$

$$F(z) = F(0)e^{-\alpha z}$$

$$\textit{normalizing to } F(0) = 1,$$

$$\frac{F(z)}{F(0)} = 0.1 = e^{-\alpha z}$$

$$\ln(0.1) = \ln(e^{-\alpha z})$$

$$-2.3 = -\alpha z$$

$$z_{90\%} = \frac{2.3}{\alpha}$$

Absorption length

- Notice that blue photons (400 nm) are stopped at less than 1 um, while infrared photons (1000 nm) can cover more than 100 um.
- Also note less temperature dependence at shorter wavelengths

Absorption length

- Si is an indirect-bandgap semiconductor, therefore two regimes can be seen with change occurring at about 2.5 eV (500 nm)
- The <u>direct</u> bandgap energy of Si is 2.5 eV
- The <u>indirect</u> bandgap energy of Si is 1.12 eV
- Above 2.5 eV, the transitions are direct
- Below 2.5 eV, the transitions are indirect

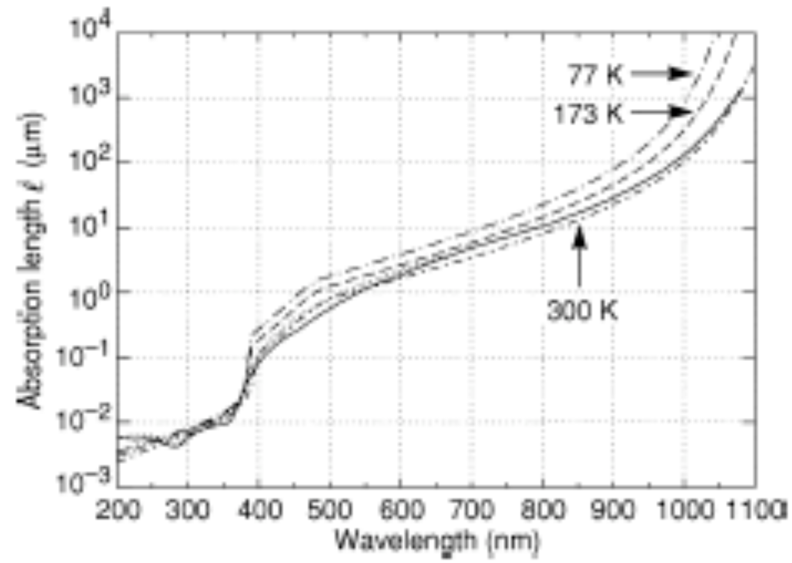
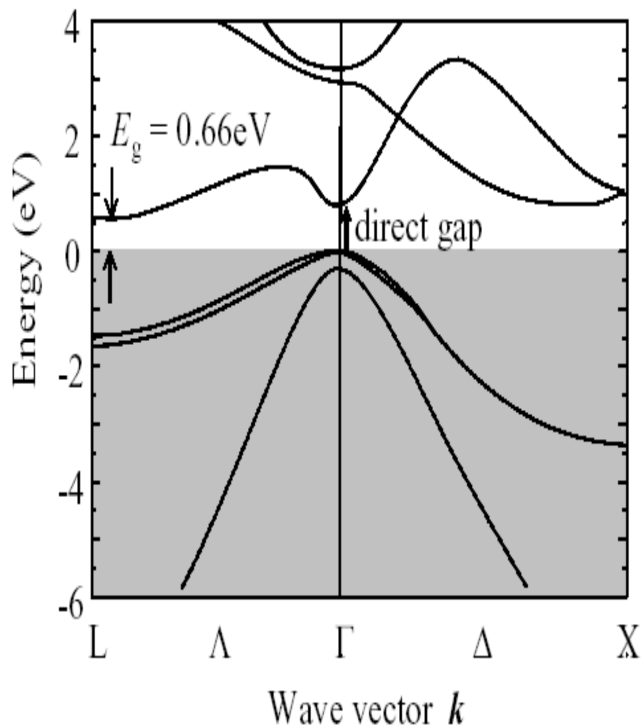
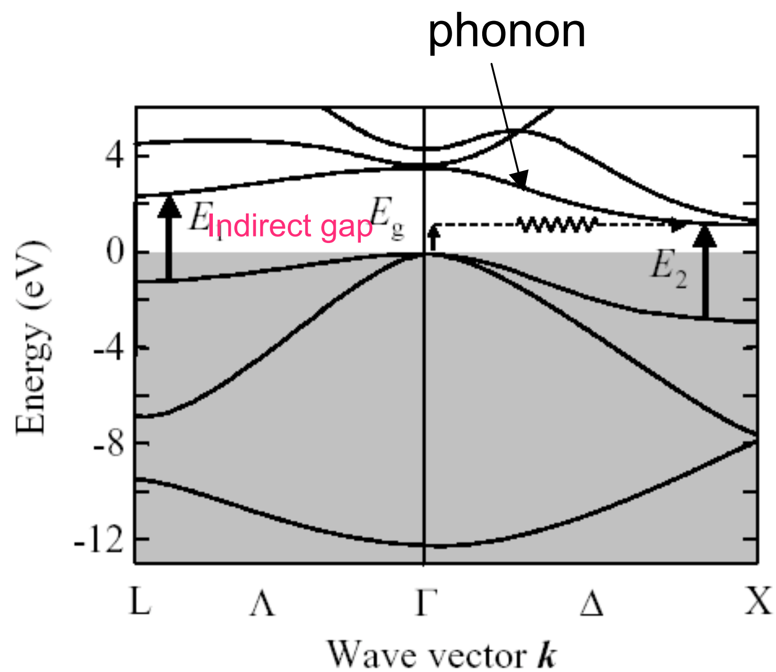


Fig. 2. Absorption length versus wavelength for silicon. Data and calculations (dashed lines) are taken from [18]. Additional room-temperature data (solid line) are taken from [1].

Direct vs. indirect bandgap materials



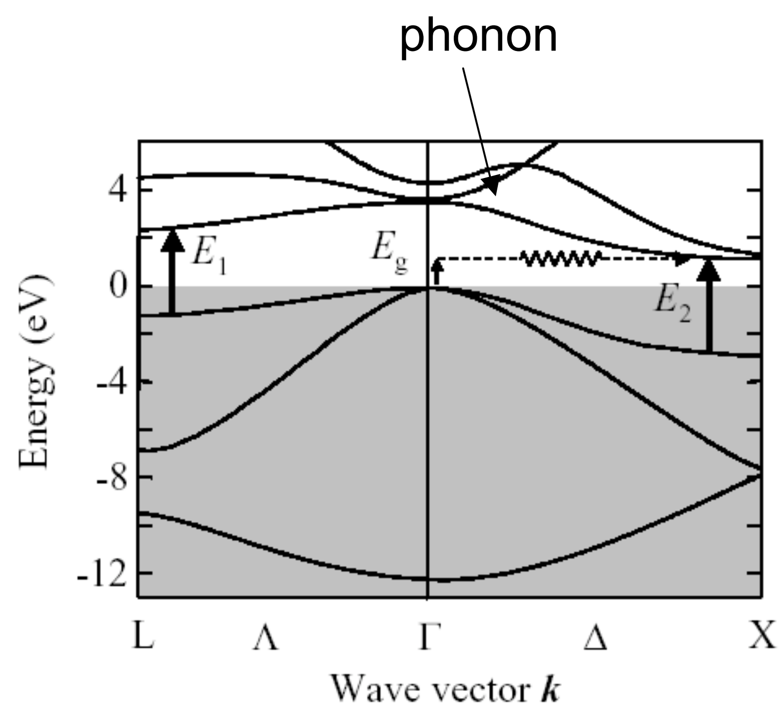


Ge is a direct bandgap material

Si is an indirect bandgap material

Direct vs. indirect transitions in Si

- Above 2.5 eV, the transitions are direct
- Below 2.5 eV, the transitions are indirect



Si is an indirect bandgap material

Direct transitions

- For photon energies above 2.5 eV, absorption is highly efficient and the absorption coefficient is determined by available conduction band states.

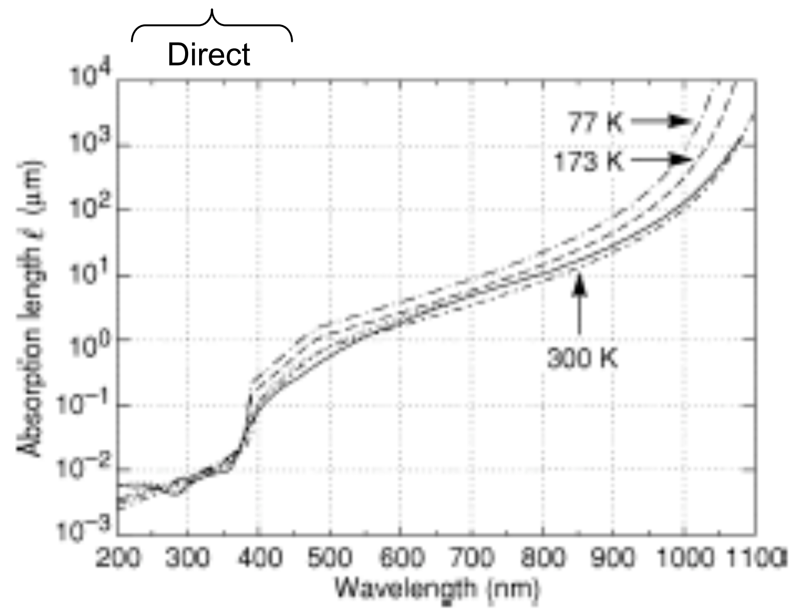
- Absorption coefficient for direct transitions, α_d, varies as square root of energy as per the energy dependence of the conduction band density of states

- Temperature dependence is weak in direct bandgap regime

$$\alpha_d = A\sqrt{h\nu - E_{g,direct}(T)}$$

A is a constant

T is absolute temp



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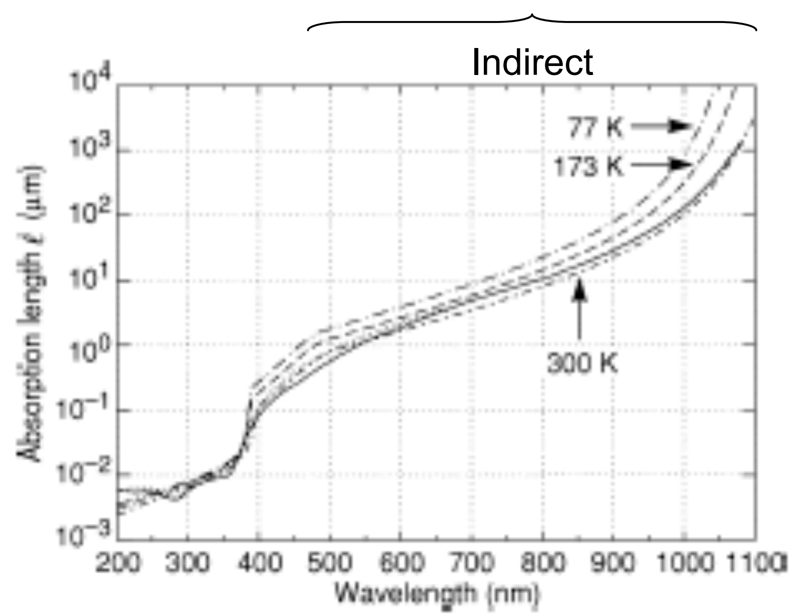
Indirect transitions

- Below 2.5 eV, phonons are required for momentum conservation
- Absorption less efficient
- More sensitive to temperature due to phonon statistics
- Absorption coefficient for indirect transitions, α_i
- The 2 terms are due to phonon absorption and emission



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Astronomical imaging

- The CCD developed by LBNL achieves high QE in the red and near-infrared by using a <u>thick</u> depleted region made possible by the use of a <u>high-resistivity</u> silicon substrate

- The high resistivity allows for fully-depleted operation (200-300um) at reasonable voltages

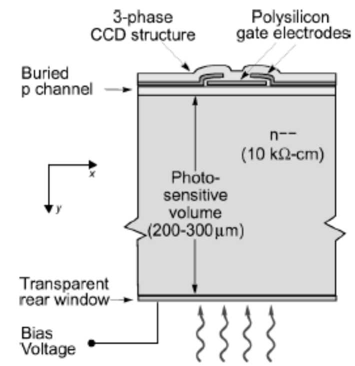


Fig. 1. Cross-sectional diagram of the CCD described in this work. The actual implementation of the substrate bias voltage connection is described in Section III.

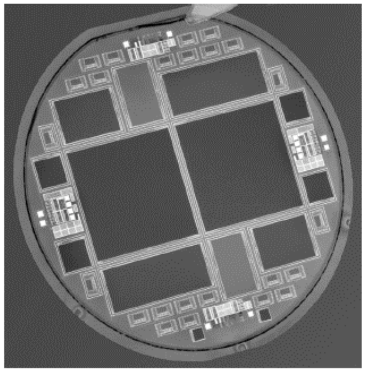
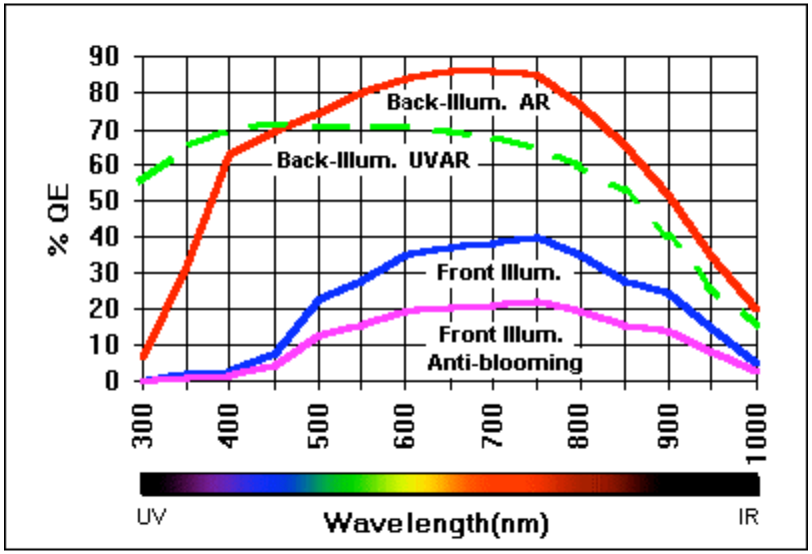


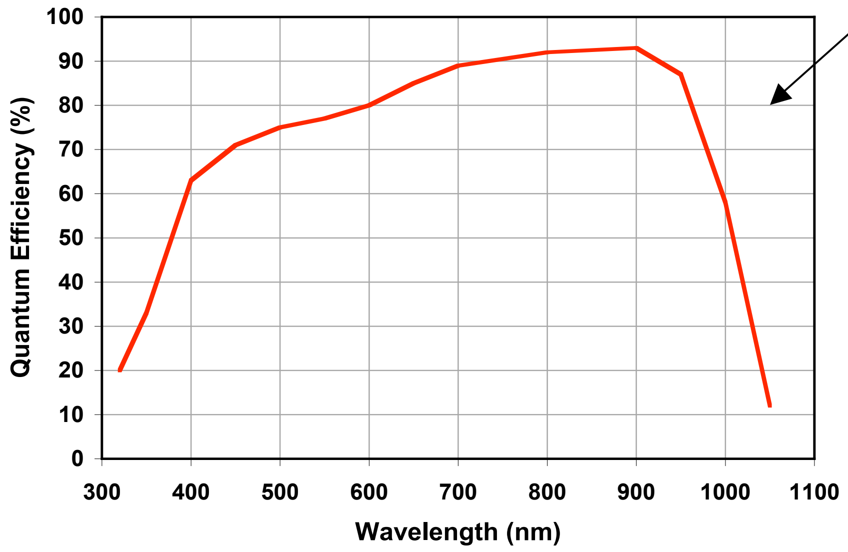
Fig. 3. A 100-mm-diameter wafer fabricated at LBNL. The two large CCDs in the center of the wafer are 2048 × 2048, 15 μm pixel, frame transfer CCDs.

QE of LBNL CCD



Typical Q.E. curves for
front- and back-illuminated CCDs

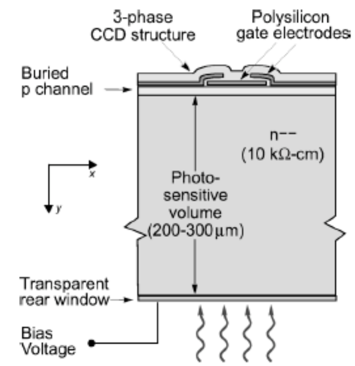
Much-improved IR sensitivity



LBNL CCD QE

Drawbacks of thick CCDs

- There are several drawbacks to a thick CCD
- Cosmic ray and terrestrial radiation sources will affect more pixels (more volume)
- More volume for dark current
- Depth of focus issues
- Light incident at large angles from the normal



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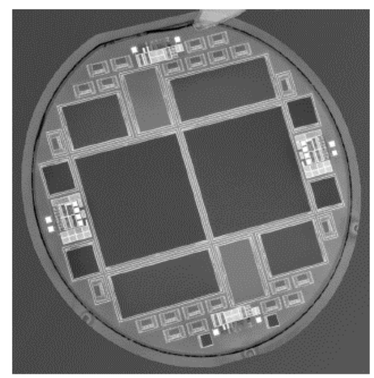

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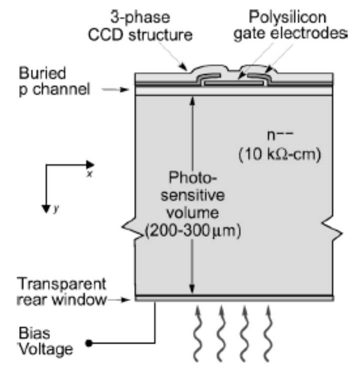
LBNL remedies to drawbacks

- LBNL CCD is p-channel (due to LBNO experience with fabrication low dark current p-i-n diodes)
  - Few e-/hour
- Degraded readout speed due to the lower mobility in p-channel is not of a concern for astronomy applications due to relatively low readout rates
- P-channel under study for space applications due to expected higher resistance to cosmic ray protons



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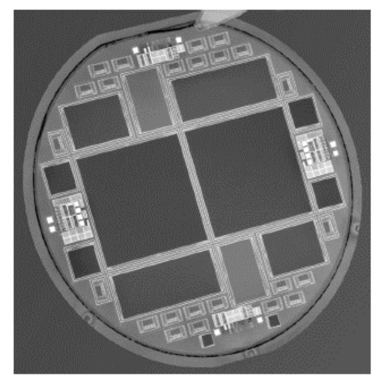

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LBNL CCD vs. Commercial CCD

- Imaging at 1 um with high QE and negligible fringing is a unique feature of a fully depleted, thick CCD.

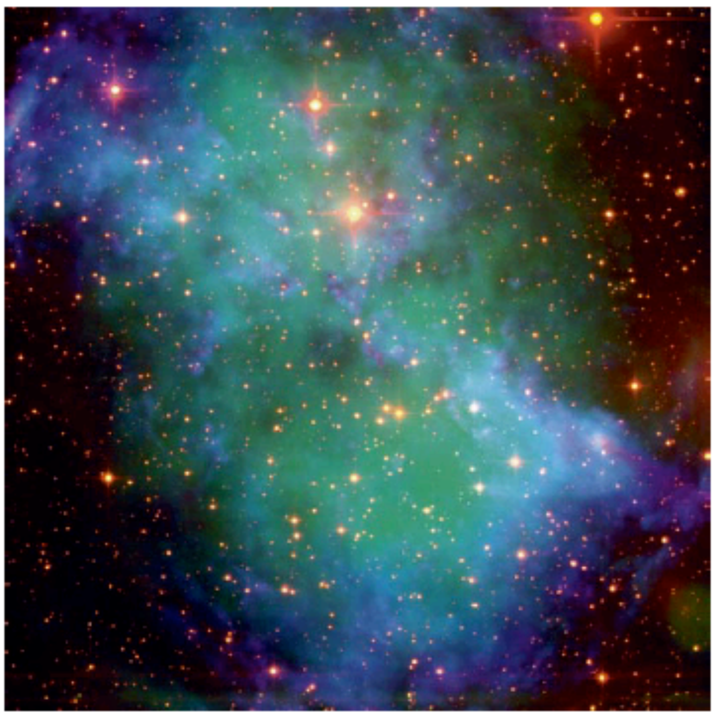


Fig. 10. Far-red/near-infrared image of M27 (Dumbbell Nebula) taken with a fully depleted, back-illuminated 2048 × 2048, 15-μm pixel, high-resistivity CCD. The image was generated from exposures taken at three wavelengths (see text) at the National Optical Astronomy Observatory WIYN 3.5-m telescope.

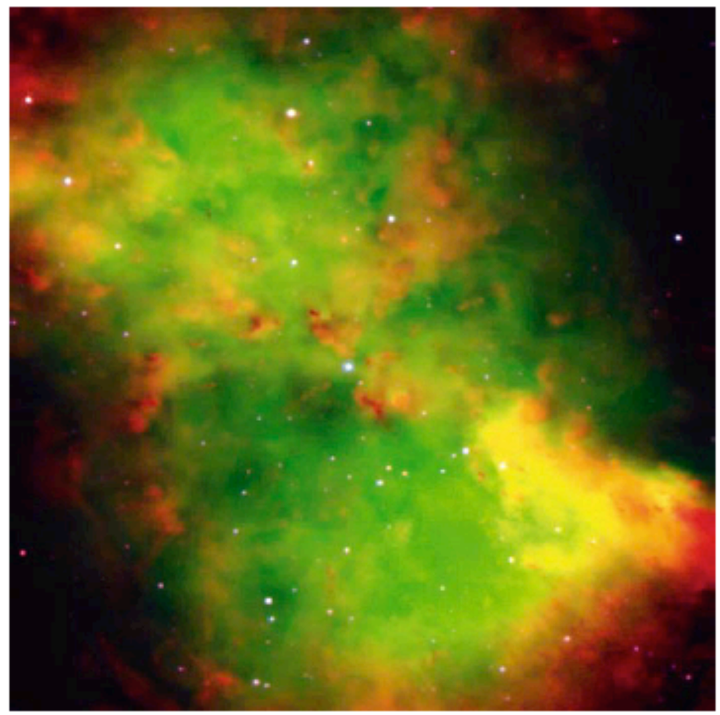
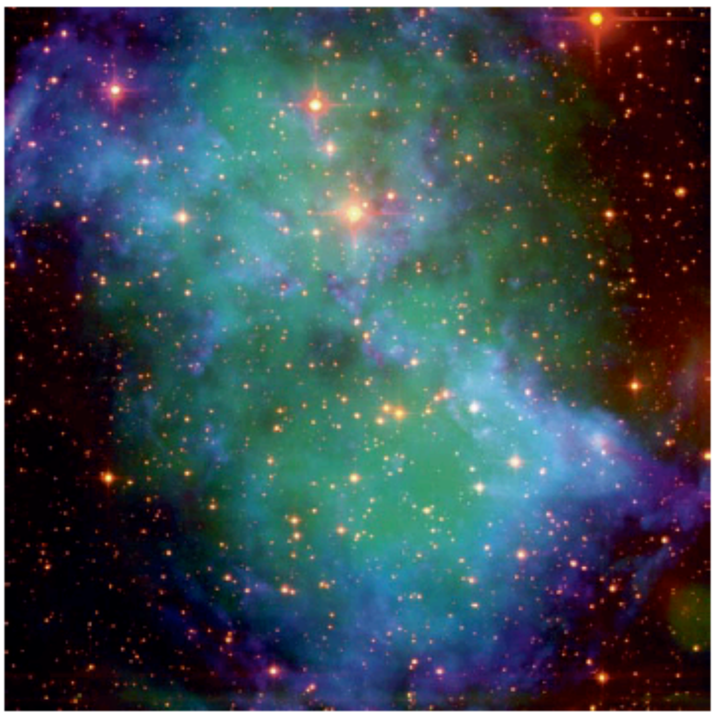


Fig. 11. Visible light image of M27 (Dumbbell Nebula) taken with a commercially available, back-illuminated 2048 × 2048, 24-μm pixel CCD. The image was generated from exposures taken at three wavelengths (see text) at the European Southern Observatory 8.2-m VLT.

LBNL CCD vs. Commercial CCD

- The main difference in the images is the detection of background stars in the 1 um exposure, which are not seen in the image of Fig. 11 due to absorption of the visible wavelengths of the background light in the dust and gas in the vicinity of the nebula.



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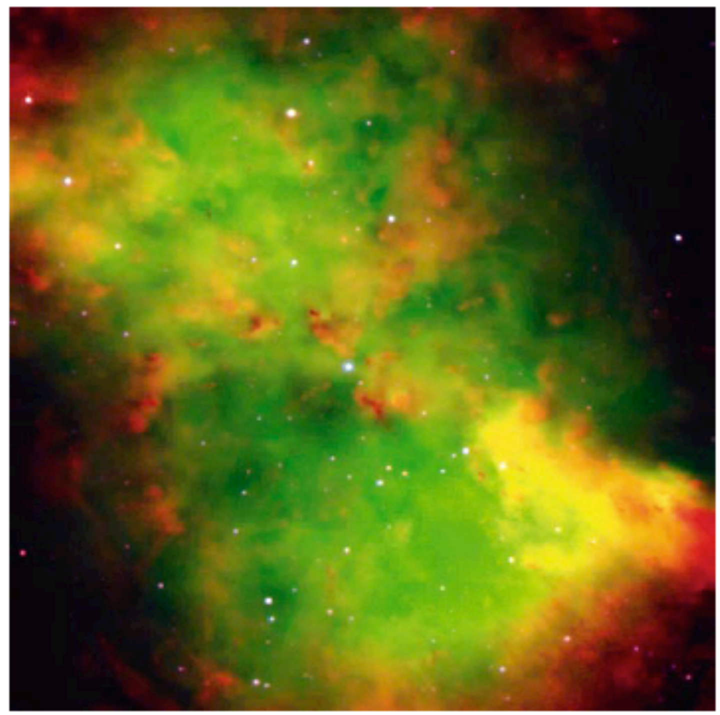

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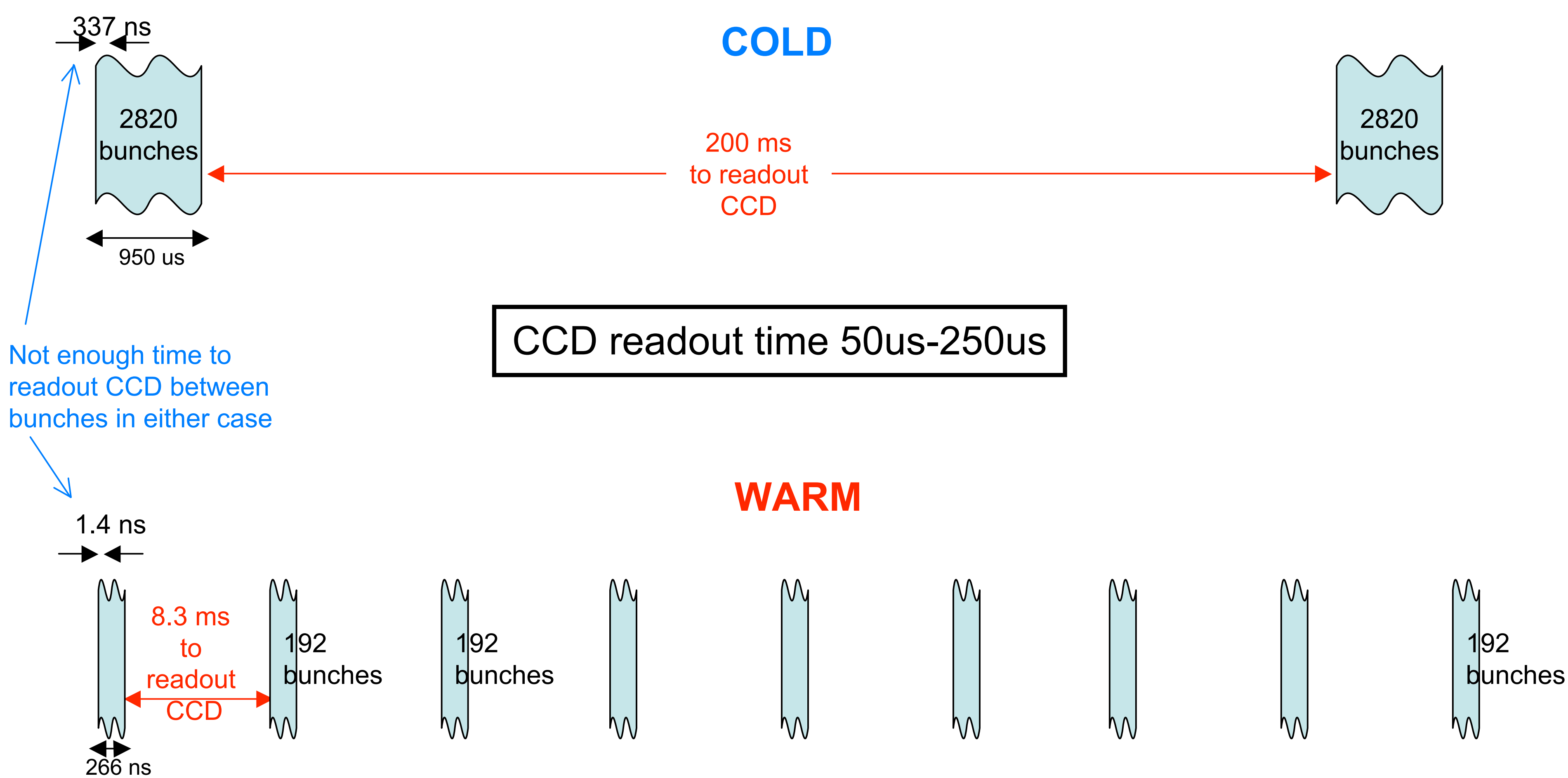
Are CCDs a viable vertex detector for a cold ILC?

Compare warm and cold timing



Compare warm and cold timing

- CCD readout time 50us-250us
- There is not enough time between bunches to readout the CCD (337ns, 1.4n). Switch to CMOS pixel technology?
- There is enough time to readout the CCD between trains (200ms, 8ms)
- But for cold technology, that would mean integrating over 2820 bunch crossings, which is far too many to sort out events!
- For warm technology, would have to integrate over "only" 192 bunch crossings, which is (would have been) permissible.

COLD

$$\frac{2820 bunches}{train}\frac{337ns}{bunch}=\frac{1ms}{train} \quad @\,5\ Hz \rightarrow \frac{200ms}{cycle}$$

WARM

$$\frac{192 bunches}{train}\frac{1.4ns}{bunch}=\frac{268ns}{train} \quad @\,120\ Hz \rightarrow \frac{8ms}{cycle}$$

Cartoon of bunches/timing on next slide →

Why not decrease SRF pulse width?

- SRF cavities take a long time to fill/drain (TTF 500us)
- Assume you'd want to be on at least as long as you are filling. Make it 1000us
- Why not longer than 1000us? Limited by rf gun and klystrons and modulators
- NRF has high peak power, leads to shorter pulses

Why not increase SRF freq

- Increase f, increase R
- Increase f, increase BCS losses
- So, R is proportional to f^2
- Increase freq, must decrease temperature